AN ABSTRACT OF THE THESIS OF

Rebecca Yang for the degree of Master of Science in Civil Engineering presented on May 9, 2016.

Title: Root Cause Analysis of Transportation Infrastructure Accidents Using Fault Trees

Abstract approved:

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The Bureau of Labor Statistics cites construction as the most hazardous industry within the United States. The construction industry was responsible for 20% of all fatal occupational injuries in 2014. Approximately 20% of the construction injuries occur within Heavy Civil Engineering, in which there are 950,000 workers employed annually. This study identifies the most frequent and severe accidents in transportation infrastructure projects and how they occur through creating fault trees and performing root cause analysis to identify the causes of these accidents. Fault tree analysis is then used to determine the major risk factors and the relationship between these risk factors and the severe accidents.
Root Cause Analysis of Transportation Infrastructure Accidents Using Fault Trees

by
Rebecca Yang

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APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Rebecca Yang, Author
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1 INTRODUCTION

The Bureau of Labor Statistics cites construction as the most hazardous industry in the United States. Figure 1.1 presents the number of fatal work injuries and the fatal work injury rate per 100,000 full-time workers in 2014. The construction industry is responsible for 874 of these fatal work injuries, which represents 20% of the fatalities in all private industries in 2014.

![Figure 1.1: 2014 Fatal Occupational Injuries by Industry (BLS, 2014)](image)

The four types of accidents that caused 58.1% of construction worker deaths in 2014 were falls, electrocutions, struck by object, and caught in/between. The ten most frequently violated OSHA standards in fiscal year 2015 included fall protection, hazard communication, scaffolding, respiratory protection, control of hazardous energy, powered industrial trucks, ladders, electrical wiring methods, components, and equipment, machinery and machine guarding, and electrical systems design. (OSHA, 2015).

Figure 1.2 shows the top ten events that led to fatalities in 2014. Transportation incidents are a leading cause of fatalities. Approximately 20% of the fatal construction injuries occur within
Heavy Civil (indicated by roadway incidents in Figure 1.2), in which there are nearly 950,000 workers employed annually (BLS, 2015).

Figure 1.2: 2014 Occupational Fatalities by Event (BLS, 2014)

Although workplace fatalities, injuries, and illnesses rates have declined by 67% since 1970, more work can be done to further improve workplace safety. Injuries do not just harm the workers in the accidents, but they also impact coworkers and company productivity. Both direct and indirect costs result from construction accidents and negatively impact construction firms. These costs lead to absences, lost productivity, permanent disability, fractures, and fatalities.

1.1 RESEARCH OBJECTIVE

The objective of this research is to determine what the most frequent and severe accidents in transportation infrastructure projects are and how they occur in order to increase safety during construction of future infrastructure projects. The identification of accidents and their causes will
be accomplished by creating fault trees and performing root cause analysis. After identifying severe and frequent accidents, major risk factors and the relationship between each risk factor and accident will be determined using fault tree analysis.
2 LITERATURE REVIEW

The following section creates a context for this study based on a literature review of articles relevant to this research topic.

2.1 COMMON ACCIDENT TYPES

The Occupational Safety and Health Administration classifies the five major accident types contributing to fatalities and serious injuries as: falls, struck by, caught in/between, electric shock, and other. Falls, struck by/against, caught in/between, and electric shock are known as the construction focus four because they are the four leading causes of death in construction. (OSHA, 2016). Falls include both falls from elevation and falls on the same level. If an impact alone creates an accident, it is considered a struck by incident. Struck by hazards include struck by flying object, struck by falling object, struck by swinging object, and struck by rolling object. If an injury results from being crushed between two objects, it is classified as caught in or caught between. Caught in or caught between incidents can be caused by cave-ins, being caught in machinery, and being crushed between objects. Electric shock can be caused by contact with overhead power lines, contact with live circuits, unkempt cords, and lightning strikes. (OSHA, 2015).

2.2 HEAVY CIVIL CONSTRUCTION

According to Pegula (2013), transportation infrastructure is a major part of Heavy Engineering and Civil Engineering. It involves the construction of bridges, roads, canals, airports, and other public projects. The heavy civil industry is considered one of the most dangerous sectors within construction because work often happens during the night. More highway construction and maintenance occurs between dusk and dawn to avoid heavier traffic. Not only does highway
construction result in the most vehicle-related accidents, but construction workers also face a variety of safety hazards such as musculoskeletal injuries from loading, unloading, and retrieving materials, slips and falls on work surfaces, getting struck by falling objects, and getting caught between heavy machinery. These hazards led to 962 fatalities on transportation infrastructure projects between 2003 and 2010 (Pegula, 2013).

Figure 2.1: 2014 Local Government Nonfatal Occupational Injuries and Illnesses by Industry (BLS, 2014)

Heavy and civil engineering construction has the third highest incidence rate of nonfatal occupational injuries and illnesses in local government industries at 8.6 per 100 full-time workers in 2014, as shown in Figure 2.1. In addition to the 8,500 injuries and illnesses within heavy and civil engineering construction, there were 170 fatalities in this sector during 2014. (BLS, 2015). Because of the hazardous nature of construction, particularly in the transportation infrastructure sector, numerous studies have proposed methods and models for reducing accidents and improving safety in the workplace.

Abdelhamid and Everett (2000) argued that accident causation and human error theories must be used to identify root causes. In their Accident Root Cause Tracing Model (ARCTM), they stated
that accidents occur because of unsafe conditions, worker response to unsafe conditions, or unsafe acts. ARCTM was applied to three accident reports from the Michigan Department of Transportation to examine whether worker training, worker attitude, or a managerial procedure should be fixed to prevent the reoccurrence of these heavy civil construction accidents.

Burke et. al. (2006) examined the effectiveness of different levels of engaging intervention methods in improving safety by investigating 95 studies from 1971 to 2003. It was found that more engaging training led to safer performance. Behavioral modeling was the most effective method followed by programmed instruction and feedback. The least effective training method was lectures, pamphlets, and videos.

Cooper and Philips (2004) asserted that perceptions of safety do not always match safety behavior. They surveyed perceptions of workplace hazards, safety hazards and self compliance, and safety participation in a manufacturing plant and discovered that the most effective method of safety was changing unsafe environments and behavior rather than training to alter attitudes and beliefs on safety.

Chi et. al. (2005) studied 9,358 accidents in US construction between 2002 and 2011 and discovered that a combination of unsafe worker acts such as misjudgment or inappropriate operation and unsafe working conditions such as an unsafe work surface or inclement weather were a major root cause for construction accidents.

Chi et. al. (2014) used graphical fault tree analysis to determine the causes of 411 fatal construction falls in Taiwan from 2001 to 2005. The data was analyzed and the causes for falls were found to be unsafe behavior, unsafe machinery and tools, and unsafe environment.

Hadiprioni (1992) used a fault-tree expert system to analyze construction falls from elevated floor openings. He argued that falls are caused by worker's enabling causes, worker's triggering causes,
naturally induced impacts, and worker’s support-related causes. Worker’s enabling causes are attitude, health, and skill-related issues. Worker's triggering causes are human-induced impacts, including impacts from equipment, materials, or another worker, and naturally induced impacts like strong winds. Worker's support-related causes are failures from structures and components that support the worker.

Though some studies utilize fault tree analysis, none of these studies have been performed in the field of transportation infrastructure construction. Most of the research that has been conducted in determining the root cause of construction accidents is theoretical, whereas the current study takes a more qualitative and practical approach in examining the risk factors involved with transportation infrastructure construction. Using data provided by the Occupational Safety and Health Administration’s (OSHA’s) Fatality and Catastrophe Investigation Summaries, we will use fault tree analysis to determine effective accident prevention strategies.

2.3 OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION (OSHA)

OSHA is an organization that enforces safety regulations and establishes safety standards. It has successfully improved safety in all occupations by reducing fatalities by 62% and injuries by 42% in the last few decades. (Hinze, 2011). There are tens of thousands of construction sites yearly but only a few thousand OSHA employees, so it is not feasible to evaluate the safety of all construction sites. OSHA compliance inspectors focus on reporting imminent dangers, investigating fatalities, addressing employee complaints, responding to agency referrals, and conducting targeted inspections. OSHA utilizes an Integrated Management Information System (IMIS) to store data from fatalities and serious injuries. OSHA compliance officers write an incident narrative and classify the incident by placing it in one of the five major accident categories.
Firms are required to record any non-minor work injuries in the OSHA 300 Log as lost-time or not lost-time injuries. This means that all injuries that require more than first aid treatment, involve medical treatment, loss of consciousness, or restriction of work and motion must be recorded. Furthermore, firms are required to report any work-related fatalities and hospitalizations of three or more individuals to OSHA. The rules on reportable cases changed in 2015, so now firms are required to report work-related fatalities, work-related in-patient hospitalizations of at least one employee, work-related amputations, and work-related losses of an eye (OSHA, 2014). Reportable cases from 1996 to 2013 in transportation infrastructure construction are used in this study.

2.4 ROOT CAUSE ANALYSIS (RCA)

Although OSHA groups fatalities by category, this alone does not provide sufficient information to determine underlying safety issues and hazards. The American Society for Quality defines a root cause as the highest level cause of a problem, which should be eliminated through process improvement (ASQ, 2016). To identify root causes, root cause analysis may be used. Root cause analysis examines root causes of events that impact safety, health, environment, quality, reliability, and production by identifying what, how, and why an incidence occurred. Suggestions may then be implemented to prevent these undesirable events from recurring. More specifically, there are four steps in RCA. First, data relevant to the event are collected. Second, causes are placed in a chart. Third, root causes are identified for each case. Fourth, recommendations are generated and implemented to reduce the likelihood of undesirable incidences from occurring (Rooney, 2004). Thus, root cause analysis is a useful tool for identifying key problem areas and feasible solutions to these issues in transportation infrastructure construction projects.
2.5 FAULT TREES

Fault trees are a deductive method of reliability and safety analysis originally developed by Bell Telephone Laboratories for the US Air Force in missile reliability analysis. These trees use a top-down approach by starting out with a main event at the top of the tree with branches leading to intermediate events then root causes at the bottom of the tree. Fault Tree Analysis (FTA) is often used in safety, reliability, and accident investigation. Fault trees can be used to effectively identify and prioritize the root causes or contributing factors of accidents and can be used to optimize the safety of systems (NASA, 2002).

Fault trees are created using Boolean algebra. Boolean "AND" and "OR" gates are used to connect root causes at the bottom of the tree structure to intermediate causes to the primary event at the top of the tree. An "OR" gate means that an event will occur if any of the "OR" events occur, while and "AND" gate means that an event will occur only if all of the "AND" events occur. An example of a fault tree is shown in Figure 2.2. This fault tree shows that the brake fails if just the brake pads fail or if the brake sensors, brake controller, and brake actuator all fail (Circular Economy Toolkit, 2016). The root causes are assigned probabilities based on their chance of occurrence. (Khakzad, 2011).
Fault tree analysis is a beneficial tool for root cause analysis because of its widespread applicability. This deductive analysis method identifies the relevant events and conditions that lead to an undesired event, determines combinations of parallel and sequential events, and models complex relationships. It also identifies critical components for safety and probabilities of events. Moreover, it is useful for determining any weak links in a system and showing where more emphasis on safety should be placed based on common failure modes. (NASA, 2002). Common methods used in fault tree analysis include the analytical method, the Monte Carlo simulation, and minimal cut set determination. (Khakzad, 2011). The method used in fault tree analysis of transportation infrastructure accidents presented herein is minimal cut set determination.
2.6 OTHER APPROACHES

Several other approaches of system reliability analysis exist in addition to fault tree analysis. A few common methods are described below.

2.6.1 Event Tree

An event tree is a bottom-up inductive method that begins with an initial event with chains of possible successes and failures for intermediate events leading to possible outcomes. In the event tree shown in Figure 2.3, possible outcomes for a fire are provided. For instance, if there is a fire and the sprinkler system fails and the call to the fire department fails, then the system will be destroyed. (Reliability Road Map, 2016).

![Event Tree Structure](image)

**Figure 2.3: Event Tree Structure (Reliability Road Map, 2016)**

2.6.2 Reliability Block Diagram

A reliability block diagram (RBD) consists of a series of blocks with failure rates associated with each of them. More specifically, there is one input block and one output block linked by intermediate blocks in series or parallel. Blocks in series are similar to events connected by "OR" gates in fault trees, meaning that if any one of the blocks in series fails, the entire system will fail. Blocks in parallel are similar to events connected by "AND" gates in fault trees, meaning that all of the blocks in parallel must fail in order for the system to fail. Figure 2.3 depicts an example of
a reliability block diagram. As shown in the example RBD, the power supply, either fan, and the processor must fail for the hard drive to fail. (ReliaWiki, 2016).

![Reliability Block Diagram](image)

**Figure 2.4 Reliability Block Diagram Structure (ReliaWiki, 2016)**

2.6.3 Fishbone Analysis

The Fishbone or Cause and Effect Diagram displays possible causes for a problem with large bones of causes branching out into smaller bones of subcauses. Figure 2.4 shows an example fishbone diagram. For the product to be contaminated with iron, there could be causes from measurement, materials, methods, environment, manpower, or machines. One possible cause related to methods could be not following the analytical procedure.

![Fishbone Diagram](image)

**Figure 2.5: Fishbone Diagram Structure (ASQ, 2016)**
3 METHODOLOGY

This study determines both root and intermediate causes of transportation infrastructure accidents. This is accomplished by examining the most serious cases from Oregon OSHA related to transportation infrastructure accidents, compiling the data in fault trees and creating corresponding minimal cut sets to organize the accident information.

3.1 CASE SELECTION

Based on geographical proximity, accident data from the Pacific Northwest region is of interest. More specifically, the accidents of interest belong in the Highway, Street, and Bridge Construction Sector (NAICS 237300) and are from projects in the Northwestern United States (Region 10 in OSHA). NAICS is the North American Industry Classification System that was developed by the US Economic Classification Policy Committee, Statistics Canada, and Mexico's Instituto Nacional de Estadística y Geografía so that business statistics could be compared across North America. It replaced the Standard Industrial Classification (SIC) System in 1997 and is the current standard federal US agencies use to classify business establishments in order to classify, analyze, and publish statistical data concerning the US economy. (NAICS, 2016). OSHA has divided the United States into ten separate regions based on geographical location. Region 10 consists of the Northwestern states of Oregon, Washington, Idaho, and Alaska.

To obtain the most out of the data, there was a focus on the most serious transportation infrastructure cases from Oregon OSHA. These serious cases are recorded by OSHA compliance officers with accident investigation summaries. OSHA requires that injuries and incidents are recorded if they involve one or more of the following: death, days away from work, restricted work, job transfer, medical treatment beyond first aid, loss of consciousness, other serious or
significant cases as diagnosed by a physician or licensed health care professional, and occupational injuries and illnesses that meet special recording criteria (OSHA, 2016).

3.2 DATA SOURCES

The data used in this study was collected from the OSHA office in Salem, Oregon. OSHA's Integrated Management Information System includes Fatality and Catastrophe Investigation Summaries that provide records of serious and fatal occupational injury cases. Serious and fatal transportation infrastructure accident cases were found from the publicly available online OSHA database and more detailed data was collected from the Salem ODOT office. OSHA first recorded accidents on microfiche more than thirty years ago. It then began preserving accident data on microfilms around 1995. In April of 2013, OSHA began to scan documents and archive them. Most of the cases used in this study were printed from microfilms as shown below, but a few cases were printed from the computer archives.
The information provided from these 105 summaries includes investigation summaries with categories of causes, accident synopsis reports, and other OSHA findings pertinent to the accidents.

### 3.3 FAULT TREE CREATION

Each case was studied in-depth and summarized to create fault trees based on the data provided by Oregon OSHA. The causes leading to each injury or fatality were first determined in a linear form using OSHA root words (defined in Appendix) by asking why something happened starting with the precursors of the accident and continuing this process of asking why up to the actual occurrence of the accident. Root words are defined as the key phrases OSHA uses to classify accidents based on the hazards present and mistakes that led to the occurrence of an incident.
Similar event types were then grouped together to create a fault tree with branches leading to intermediate causes and ultimately, the root cause(s) for each event. Because not enough information was provided using solely root words, non-root words were added to the trees to help improve understanding and eliminate any gaps between intermediate and root causes.

Probabilities were calculated for each root cause based on frequency using descriptive statistics. To elaborate, the number of OSHA cases attributed to a specific cause was divided by the total number of OSHA cases examined for each fault tree. Several fault trees from literature assign probabilities based on frequency, exposure, and severity, but it is difficult to measure the exposure and severity based on the information provided by the Fatality and Catastrophe Investigation Summaries. There is no information provided on the worker-hours prior to the accident, so exposure cannot be calculated. Severity is a difficult standard to measure because it is subjective to the victim’s pain threshold and relative to the incidents of other victims. For example, it is uncertain whether a concussion based on a fall and misjudgment is more severe than a concussion from being struck by a falling object.

3.4 MINIMAL CUT SETS

The traditional fault tree includes not only the tree itself but also minimal cut sets. Minimal cut sets (MCS’s) supplement fault trees by creating a deeper understanding between causes and events. Minimal cut sets show the minimum causes that must occur for the main event to arise and provide a reliable indication of a tree's vulnerability. The smaller the cut set, the fewer the circumstances that need to be present for an accident to occur. Therefore, smaller cut sets pose a greater risk of generating an unwanted main event, so more focus should be placed on the smaller cuts to improve safety. MCS’s are extremely useful for explaining complex fault trees. (Kececioglu, 1991).
4 RESULTS

The following section depicts the created fault trees and minimal cut sets for common accident types.

4.1 FAULT TREES

The following fault trees represent a total of 105 OSHA cases in the struck by/against, fall, caught in/between, and shock categories, as shown in Figure 4.1. In the fault trees pictured in Figures 4.2 to 4.5, dashed blue lines represent AND while solid black lines represent OR. The AND causes are the adjoining boxes. For instance, Figure 4.2 shows that the first two adjoining causes, misjudgment and miscommunication, together lead to pinch point action. Each root cause box contains the cumulative incidence rate based on the OSHA cases in this study. For AND root causes, the probability is equally distributed between the root causes. For instance, the probability that the root cause is based on misjudgment and miscommunication in Figure 4.2 is 2/54 for misjudgment and 2/54 for miscommunication or 2/27 for a combination of the two.

Figure 4.1: Breakdown of Common Accident Types
As shown in Figure 4.2, the intermediate causes for caught in/between accidents are pinch point action, exited machine, hazardous worksite, flammable exposure, flying object, inappropriate procedure, and faulty equipment.
As shown in Figure 4.3, the intermediate causes for falls are poor layout, faulty structure, inappropriate procedure, flying object, and falling object.
Figure 4.4: Fault Tree for Struck By/Against Accidents

As shown in Figure 4.4, the intermediate causes for struck by/against accidents are flying object, squeeze point action, falling object, falling equipment, and poor layout.
As shown in Figure 4.5, the intermediate causes for electric shock are contacted power line and misjudgment.
4.2 MINIMAL CUT SETS

The minimal cut sets found for this study varied from two-cause to four-cause. If a cut set is two-cause, it requires a minimum of two causes to occur. For instance, Table 4.2 shows that a caught in/between incident will occur if a pinch point action exists in combination with misjudgment.

Table 4.1: Possible Causes for Caught In/Between Incidents

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Frequency</th>
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<tr>
<td>Basic</td>
<td>Misjudgment</td>
<td>18/54</td>
</tr>
<tr>
<td>Basic</td>
<td>Miscommunication</td>
<td>2/54</td>
</tr>
<tr>
<td>Conditional</td>
<td>Lack of Engineering Controls</td>
<td>15/54</td>
</tr>
<tr>
<td>Basic</td>
<td>Inappropriate Position</td>
<td>9/54</td>
</tr>
<tr>
<td>Basic</td>
<td>Insufficient Training</td>
<td>5/54</td>
</tr>
<tr>
<td>Basic</td>
<td>Inadequate PPE</td>
<td>5/54</td>
</tr>
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</table>

Root causes for accidents can be classified as basic or conditional. Basic causes are behavioral and can be avoided by the worker. Conditional causes are created from environmental conditions or poor designs and cannot be fixed by the worker alone. Table 4.1 shows that misjudgment is the most frequent cause of caught in/between accidents. Most of the causes for caught in/between are basic, while the only conditional cause is lack of engineering controls.
The minimal cut sets for caught in/between incidents range from two-cause to four-cause. Emphasis should be placed on avoiding a combination of the two-cause cut sets because these are more likely to occur. The four-cause cut set of exited machine, misjudgment, insufficient training,
and inadequate PPE is least likely to occur because all four of these events must be in place in order for an accident to arise.

**Table 4.3 Possible Causes for Falls**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Inadequate PPE</td>
<td>6/44</td>
</tr>
<tr>
<td>Basic</td>
<td>Miscommunication</td>
<td>4/44</td>
</tr>
<tr>
<td>Basic</td>
<td>Inappropriate Position</td>
<td>4/44</td>
</tr>
<tr>
<td>Basic</td>
<td>Inappropriate Procedure</td>
<td>4/44</td>
</tr>
<tr>
<td>Conditional</td>
<td>Lack of Engineering Controls</td>
<td>2/44</td>
</tr>
<tr>
<td>Basic</td>
<td>Insufficient Training</td>
<td>8/44</td>
</tr>
<tr>
<td>Basic</td>
<td>Misjudgment</td>
<td>16/44</td>
</tr>
</tbody>
</table>

Table 4.3 shows the most frequent cause of falls is misjudgment, whereas the least likely and only conditional cause of falls is lack of engineering controls.
The minimal cut sets for falls are either two-cause or three-cause. Based on Table 4.4, eliminating misjudgment and poor layout would prevent most falls from occurring.
Table 4.5 Possible Causes for Struck By/Against Incidents

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Insufficient Training</td>
<td>7/41</td>
</tr>
<tr>
<td>Basic</td>
<td>Inappropriate Position</td>
<td>2/41</td>
</tr>
<tr>
<td>Basic</td>
<td>Inadequate PPE</td>
<td>1/41</td>
</tr>
<tr>
<td>Conditional</td>
<td>Hazardous Worksite</td>
<td>1/41</td>
</tr>
<tr>
<td>Basic</td>
<td>Misjudgment</td>
<td>15/41</td>
</tr>
<tr>
<td>Basic</td>
<td>Inappropriate Procedure</td>
<td>12/41</td>
</tr>
<tr>
<td>Basic</td>
<td>Miscommunication</td>
<td>2/41</td>
</tr>
<tr>
<td>Conditional</td>
<td>Inadequate Design</td>
<td>1/41</td>
</tr>
</tbody>
</table>

Table 4.5 shows that the most common cause of struck by/against incidents is misjudgment. Less likely causes of struck by/against accidents are inadequate PPE, hazardous worksite, and inadequate design. There are two types of conditional root causes for this scenario. Both a hazardous worksite and an inadequate design may lead to struck by/against incidents.
The minimal cut sets for struck by/against incidents can be classified as two-cause or three-cause. Based on Table 4.6, eliminating flying objects, falling objects, and faulty equipment would prevent most struck by/against incidents from occurring.
Table 4.7 Possible Causes for Electric Shock

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>No Spotter</td>
<td>18/90</td>
</tr>
<tr>
<td>Basic</td>
<td>Miscommunication</td>
<td>14/90</td>
</tr>
<tr>
<td>Basic</td>
<td>Misjudgment</td>
<td>15/90</td>
</tr>
<tr>
<td>Conditional</td>
<td>Hazardous Worksite</td>
<td>15/90</td>
</tr>
<tr>
<td>Basic</td>
<td>Insufficient Training</td>
<td>8/90</td>
</tr>
<tr>
<td>Conditional</td>
<td>Poor Layout</td>
<td>2/90</td>
</tr>
<tr>
<td>Basic</td>
<td>Inappropriate Procedure</td>
<td>18/90</td>
</tr>
</tbody>
</table>

Table 4.7 shows that the leading causes of shock are not having a spotter and utilizing an inappropriate procedure. The least likely cause of electric shock is having a poor layout. There are two types of conditional root causes for this scenario. Both a hazardous worksite and a poor layout may lead to struck by/against incidents.

Table 4.8 Minimal Cut Sets for Electric Shock

<table>
<thead>
<tr>
<th>Three-Cause</th>
<th>Four-Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Line, No Spotter, Miscommunication</td>
<td></td>
</tr>
<tr>
<td>Power Line, Misjudgment, Hazardous Worksite</td>
<td></td>
</tr>
<tr>
<td>Power Line, No Spotter, Insufficient Training</td>
<td></td>
</tr>
<tr>
<td>Misjudgment, Insufficient Training, Miscommunication, Poor Layout</td>
<td></td>
</tr>
<tr>
<td>Misjudgment, Inappropriate Procedure</td>
<td></td>
</tr>
</tbody>
</table>
The minimal cut sets for electric shock are either three-cause or four-cause. Emphasis should be placed on avoiding the three-cause cut sets because they are more likely to occur. Based on Table 4.8, using a spotter and proper judgment will prevent most shocks from occurring.
5 DISCUSSION AND ANALYSIS

The following section analyzes the fault trees, possible causes, and minimal cut sets. This section also includes validation of the fault trees based on literature reviews and other cases.

5.1 OBSERVATIONS AND TRENDS

5.1.1 Caught In/Between Incidents

Some common hazards for caught in/between cases are unguarded machinery, cave-ins, and pinned between. As shown in the fault trees, possible causes, and minimal cut sets (Figure 4.2, Table 4.1, and Table 4.2) for the caught in/between cases, misjudgment was the most common cause, contributing to almost half of the incidents. Lack of engineering controls and inappropriate positioning are other common risk factors. Inappropriate positioning may occur near pinch points. These points are locations where a body part may be caught between objects. Elimination of this risk will drastically reduce the probability of occurrence for a caught in/between incident.

5.1.2 Falls (From Elevation)

Fall hazards are abundant on construction sites. They consist of any surface that may create slipping or falling hazards. Fall protection was the most frequently cited OSHA standard in 2015, and ladder safety was the 7th most frequent citation. Fall protection is required when performing construction above 6 feet from the ground. As shown in the fault trees, possible causes, and minimal cut sets in Figure 4.3, Table 4.3, and Table 4.4, misjudgment is the main area of concern for falls from elevation.

5.1.3 Struck By/Against Incidents

Struck by hazards include flying, falling, swinging, and rolling objects. Misjudgment and inappropriate procedure were found to be the main causes for these accidents. The fault trees,
possible causes, and minimal cut sets in Figure 4.4, Table 4.5, and Table 4.6 illustrate that struck by/against usually occurs when there is faulty equipment or inappropriate use of equipment.

5.1.4 Electric Shock Incidents

Electric shock hazards include power lines, energized sources, and cords. From the fault trees, possible causes, and minimal cut sets in Figure 4.5, Table 4.7, and Table 4.8, inappropriate procedure and lack of a spotter were the leading causes for shock, closely followed by miscommunication, misjudgment, and a hazardous worksite. Most shocks occurred when working near overhead power lines and machines contacted these lines.

5.2 MODEL VALIDITY

The validity of these models was tested using findings from previous research and additional accident cases that were not used in creating the fault trees. Previously performed work providing lists of the most common causes for the five common accident types of falls, struck by, caught in/between, electric shock, and other were compared to results from this study.

Chi (2005) examined common causes for falls and obtained similar results to those found in our fault tree analysis. The most common causes for falls through floor openings were unguarded openings, inappropriate protections, and protection removal. Falls from structural elements were caused by bodily actions and improper PPE use. Falls from roof edges were caused by bodily actions and tools. Falls through roof surfaces were caused by defective scaffolding. Falls from ladders were caused by overexertion and unsafe equipment. Falls down stairs were caused by unguarded openings. Falls to a lower floor were caused by poor work practices. Effective primary fall protection consists of fixed barriers, whereas secondary fall protection consists of fall arrest devices and systems.
Results from the fault tree models in Figures 4.2 through 4.5 showed that the root causes for falls are inadequate PPE, miscommunication, lack of engineering controls, insufficient training, poor layout, and misjudgment. Inadequate PPE is similar to inappropriate protection and protection removal in Chi's study. Lack of engineering controls is similar to defective scaffolding, unsafe equipment, and unguarded openings. Insufficient training is comparable to poor work practices, and an example of poor layout is unguarded openings. The words used in these models differ from those in Chi's study because this study mostly uses OSHA root words.

Chi (2009) also analyzed electrical fatalities in construction. Five major causes of electrocutions were direct worker contact with energized power lines, boom contact with overhead power lines, conductive equipment contact with power lines, worker contact with energized equipment, and defective equipment.

Results from the fault tree for electric shock (Figure 4.5) showed that root causes were having no spotter, miscommunication, misjudgment, a hazardous worksite (working under/near power lines), insufficient training, and poor layout. An intermediate cause in this model was contacted power line, which included direct worker contact with energized power lines, boom contact with overhead power lines, conductive equipment contact with power lines, and worker contact with energized equipment from Chi's study.

A sample of 42 NIOSH Case Studies from other states was selected to ensure that the fault tree models apply for different cases and situations in addition to those sampled from Oregon OSHA. The distribution of NIOSH cases (shown below) in the focus four was similar to that of the OSHA cases, with both having around 40% struck by/against cases.
Testing these 42 NIOSH fatality cases on the fault trees created using OSHA accidents proved the legitimacy of the fault trees, as the root and intermediate causes fit cases from both NIOSH and OSHA organizations. Therefore, the fault trees provide verifiable causes that lead to severe accidents.
6 SOLUTIONS AND APPLICATIONS

The following section discusses solutions for the four fatal hazards and proposes applications based on the fault tree and literature study.

6.1 FATAL FOUR HAZARD SOLUTIONS

To make transportation infrastructure safer, alternative methods using the hierarchy of controls should be used. While it is most effective to eliminate hazards, this solution is not always possible or feasible. When hazards cannot be eliminated, the steps in the hierarchy of controls should be followed starting from the top and working toward the bottom of Figure 6.1. First try to substitute the hazard, and then try to isolate the hazard. If neither of these controls works, implement administrative controls, and finally use personal and protective equipment. Following these steps can reduce risks and make construction safer.

![Hierarchy of Controls](image)

Figure 6.1: Hierarchy of Controls (CDC, 2015)
Effective methods for reducing the occurrence of the four main types of construction accidents are described below.

6.1.1 Reducing Caught In/Between Accidents

While caught in/between accidents have decreased by approximately 20% in the last decade due to the decreased number of cave-ins, they are still one of the top four accidents that occur in construction. Prevention methods for caught in/between accidents include being cautious when working in excavations or confined spaces and securing or guarding machinery. PPE can also be worn to increase visibility to the operator so they may more easily avoid workers. (OSHA, 2010).

6.1.2 Reducing Falls (from Elevation)

An average of 150 to 200 fatalities and over 100,000 injuries result from falls on construction sites each year. Common methods of fall protection include the use of safety nests and fall arrest devices. These methods prevent the worker from falling too far. Fall prevention systems are even more effective as they prevent falling from occurring. Guard rails are an example of a common fall prevention system. (OSHA, 2010).

6.1.3 Reducing Struck By/Against Accidents

400 fatalities resulted from struck by/against accidents in 2010. Staying clear of fixed or moving objects and machinery, routinely checking and maintaining equipment, and wearing high visibility vests and PPE can reduce the chances of struck by/against accidents from occurring. (OSHA, 2010).
6.1.4 Reducing Electric Shock Accidents

An average of 150 fatalities result from construction electrocutions each year. Most of these deaths are caused by working on or near live wires. Remaining alert and aware of electrical hazards and utilities while working can help protect workers against electrocution. In addition, using the lock out/tag out method and staying at least ten feet away from energized power lines will prevent shock. (OSHA, 2010).

6.2 APPLICATION

Through scrutinizing a multitude of transportation infrastructure construction accidents, specific risk factors that contribute to severe accidents have been discerned and displayed in fault trees. These graphical representations portray recurring trends and their corresponding probabilities that lead to construction accidents. By being aware of these common causes, construction companies can work more safely and prevent fewer accidents from occurring in the future.

This study was performed using data from Oregon OSHA, so the findings relate most closely to transportation infrastructure projects in the state of Oregon. However, the results from this research can also be applied to other types of construction projects within the United States.

By combining the findings from the four fault trees with the knowledge from existing literature, these fault trees can be effectively used to improve heavy civil construction. Jorgenson (2016) states that intermediate causes consist of unsafe conditions, unsafe acts, and chance such as the design of work, surroundings, products, and equipment as well as slips and mistakes. He declares that root causes consist of inexperience and lack of training such as gaps in understanding, inadequacies in skill, and lack of prioritization. Therefore, the common risk factor of misjudgment
in all four fault trees may be caused by a lack of experience and training. To remedy this root
cause, Jorgenson recommends observing, evaluating, and acting. For example, observe if the
employee has the appropriate knowledge and skills for the task, evaluate whether more training
and instruction is needed, and act competently from the additional training and instruction.

Reiman (2012) asserts indicators can provide valuable insight into the performance of an
organization and the motivation of its employees. Drive indicators like management and leadership
can measure organizational safety priorities and culture. Monitor indicators like hazard and safety
understanding reflect the organization's ability to perform safely. Outcome indicators measure the
safety of the company through variables like accident rates. One drive indicator area is proactive
safety development. This is measured by reporting and analyzing incidents, performing routine
safety checks, and analyzing trends and root causes related to safety. Managing the indicators
pertinent to the common risk factors identified by the fault trees will improve safety within the
construction industry.

6.2.1Caught In/Between Accident Prevention

The intermediate causes in the fault trees are factors and conditions present on site, which
contribute to construction accidents. The presence of pinch points, defined as points other than the
point of operation where it is possible for part of the body to be caught between moving or
stationary equipment, contributed to 14 of the 27 caught in/between accidents. Misjudgment was
a root cause for all cases regarding pinch point action. Training may help workers stay aware of
these pinch points in order to properly avoid them. Other root causes for pinch points included
miscommunication, lack of engineering controls, and an inappropriate position. When working
near equipment, workers should maintain verbal or physical communication with operators to
ensure their safety and well-being. Using proper engineering controls will prevent unexpected movement of machinery. Workers should be cognizant of their surrounding and avoid positioning themselves between pinch points when working. Exiting a machine caused the fatality of one Oregonian construction worker. He did not receive adequate training nor was he wearing the required PPE, which caused him to react incorrectly by misjudging the severity of the situation and exiting the machine. When working on a hazardous worksite cannot be avoided, engineering controls should be present to make the worksite safer and reduce the probability of accidents. If flammable or flying objects are near, ensure to position yourself away from these objects and use good judgment to maintain a safe distance from these hazards. Workers sometimes fail to follow the appropriate procedure due to behavioral aspects, but from these cases, it was caused by a lack of training. Proper training is incredibly effective at educating workers on the proper and safe methods to perform work. Another cause of caught in/between incidents is the use of faulty equipment. Equipment should be maintained regularly and checked prior to use. In addition, workers should wear appropriate PPE and position themselves in safe locations relative to machinery. To prevent caught in/between accidents, examine the environment for any immediate causes that may be present. If these intermediate causes cannot be eliminated, eliminate the corresponding root causes and work cautiously around the hazards.

6.2.2 Fall Prevention

Intermediate causes for falls comprised of a poor layout, faulty structure, inappropriate procedure, and flying and falling objects. If these intermediate causes cannot be eliminated, eliminate the corresponding root causes and work cautiously around the hazards. The hierarchy of controls states that hazards should be eliminated if possible. Poor layouts created half of the falls. If the construction site layout cannot be rearranged, additional measures must be taken. Workers need
to be extra cautious and wear appropriate PPE, communicate hazards to one another, work ergonomically, follow stated procedures, and stay alert to use proper judgment. A faulty structure is another cause of falls. Structural integrity of members should be evaluated and proper engineering designs should be followed. In addition, engineering controls should be in place and proper PPE should be warn in case of emergencies. Inappropriate procedures may also lead to falls due to insufficient training or a failure in judgment. These can be remedied through additional training or supervision from an experienced worker. Flying and falling objects are possible hazards on construction sites. When working at height, it is important to be aware of the surrounding environment and any objects that may impale workers.

6.2.3 Struck By/Against Accident Prevention

Intermediate causes for struck by/against accidents are pinch and squeeze point actions, flying and falling objects, faulty equipment, and poor layout. Falling and flying objects were the most frequent intermediate causes. Workers can avoid being struck by these objects through using good judgment, especially on hazardous worksites, following the correct procedure and assuming a safe, appropriate position for the task, using PPE, and ensuring there is a reliable design for the project. Faulty equipment increases the likelihood of struck by/against accidents can be prevented by properly training workers on machinery operation. A poor layout also makes struck by/against accidents more likely, so proper judgment should be utilized if it is not possible to rearrange the layout to make work safer and more efficient. Pinch points lead to struck by/against accidents when there is insufficient training, so the worker does not know what procedure to follow to safely operate the machinery. Squeeze points lead to struck by/against accidents when appropriate judgment and clear communication are not used.
6.2.4 Shock Prevention

The intermediate causes of shock are contacting power lines and misjudging hazardous situations. When working near live or energized lines, maintaining a spotter, clearly communicating with other workers, and having the appropriate training to accurately judge the distance from power lines can avoid shock. A spotter can clearly convey the distance an operator must stay from overhead lines to remain safe and keep other nearby workers out of danger. Misjudgment is another cause that can readily be avoided to prevent shocks. By thoroughly training workers before they start work around electrical hazards, they can follow effective procedures such as lock out/tag out and communicate hazards to other workers.

The fault trees created for this study have illustrated the risks that lead to severe accidents. It is most effective to eliminate all the risks, but the minimal cut sets show the combination of risks that may occur. Eliminating one or more risks from the cut sets is another method of accident prevention. This study based on historical accident cases may be used proactively to prevent future accidents in transportation infrastructure construction.
7 CONCLUSION AND RECOMMENDATIONS

The following section summarizes the findings of this research based on the three main objectives identified in Section 1. It then provides suggestions for future direction in this research.

7.1 IDENTIFIED COMMON ACCIDENT TYPES IN TRANSPORTATION INFRASTRUCTURE

The most common accident types in transportation infrastructure projects are the same as the fatal four in the construction industry as a whole. They are falls, caught in/between, struck by/against, and electric shock. Out of the 105 heavy civil construction accidents studied, it was found that 41 accidents in Oregon were struck by/against, 27 accidents were caught in/between, 22 accidents were falls from elevation, and 15 accidents were electric shocks.

7.2 IDENTIFIED FACTORS FOR MOST FREQUENT AND FATAL ACCIDENT TYPES

The fault trees indicate the main risk factors of fatal and frequent accidents in heavy civil construction within Oregon are misjudgment and inappropriate procedures. Other leading risk factors include lack of engineering controls, inappropriate positioning, lack of a spotter, miscommunication, and a hazardous worksite.

7.3 DEVELOPED FTA MODELS

These fault trees were created using OSHA accident cases from transportation infrastructure construction in Oregon and verified through a comparison of relevant case studies and testing fatal cases from NIOSH FACE Reports on the models. Fault tree analysis depicted the minimal cut sets
for each tree, which shows the combination of risk factors that leads to a severe accident in the heavy civil industry.

7.4 FUTURE STEPS

Fault trees have been created and analyzed for transportation infrastructure construction in Oregon. This study could be expanded by examining transportation infrastructure accidents in other states or even other countries. It could also be expanded by including commercial and residential construction. The validity of the models has been tested using construction fatality reports, but it would be interesting to apply these fault trees to current heavy civil construction projects to see their effect on safety.
8 REFERENCES


9 APPENDICES

9.1 ANNOTATED BIBLIOGRAPHY


Various models used for the identification of root causes of construction accidents are mentioned such as the accident root cause tracing model, Heinrich’s domino theory, multiple causation model, accident proneness theory, and Ferrel theory.

Accident root causes tracing model (ARCTM) for the construction industry states that accidents occur because of three root causes: 1) failing to identify an unsafe condition, 2) proceeding with work despite unsafe conditions, and 3) behaving unsafely. ARCTM states that unsafe conditions are caused by: 1) management action/inaction, 2) unsafe worker/coworker acts, 3) non-human related events, and 4) unsafe conditions that are a natural part of initial site conditions. Three injury cases were analyzed using ARCTM.

In Heinrich’s Domino Theory, there are five dominoes: 1) ancestry and social environment, 2) fault of person, 3) unsafe act and/or mechanical/physical hazard, 4) accidents, and 5) injury. If one domino falls, this leads to a domino effect and causes all the dominoes to fall. Heinrich states that people are the reason for accidents, and management is responsible for preventing the occurrence of accidents.

The Multiple Causation model argues that many factors combine in a random manner to cause accidents. Permanent improvement can be achieved by determining the root causes.

Accident Proneness Theory states that permanent characteristics inherent in an individual make them more likely than others to have an accident.
Ferrel Theory believes accidents are a causal chain of events, significantly affected by human error. Human errors are caused by: 1) overload, 2) incorrect response, and 3) improper activity. Asking why can help determine intermediate and root causes of accidents and determine prevention techniques.


A fault tree analysis of construction defect causes was performed based on frequency and magnitude for four residential projects in Dubai. Frequency is measured by Fussel-Veseley, while magnitude is measured by Birnbaum importance. Reason’s Swiss Cheese Model is applied to defects. This theory states that the causes of accidents weaken the defense layers within a system and thus increase the possibility of an accident. There are four layers of Swiss cheese. There are root causes, which include organizational influences, defective supervision, and preconditions for defective acts. There are also direct causes, which are defective acts. Weighted probabilities are estimated for various causes for use in the fault tree.


Primary accident causes include incorrect work practices, unsafe operation, and poor machine design or condition/guarding. The UK Health and Safety Executive (1995) states that emergency
stopping devices can greatly decrease risk. OSHA (1992) requires impediment from uncontrolled or undesired machine movement. Etherton (1987) proposed some safeguards related to human factor such as fixed barriers, enclosures, interlocks, pullouts, push buttons, lock outs, and emergency stops. Kjellen (1990) proposed training, attitude change, organizational change (good housekeeping, safe methods and instructions, and maintenance) as well as alarms, safeguards, zoning, signaling, and PPE. Lind (2008) recommended safe methods, hazard identification, equipment and workplace condition, and proper tools. Useful risk assessment tools include hazard identification checklists, guides, guidance, handbooks, and questionnaires. Preventative measures may be technical, procedural, or behavioral and influence the hardware, organization, or human.


The effectiveness of different levels of engaging intervention methods on improving safety and reducing accidents, injuries, and illnesses was examined based on 95 studies from 1971 to 2003. There are three different levels of intervention methods: 1) least engaging (lectures, pamphlets, and videos), 2) moderately engaging (programmed instruction and feedback), and 3) most engaging (behavioral modeling and hands-on training). More engaging training is more effective in increasing safety performance.

Chi examines common causes for falls and breaks this data into sections by age, gender, experience, and company size. The most common causes for falls through floor openings were unguarded openings, inappropriate protections, and protection removal. Falls from structural elements were caused by bodily actions and improper PPE use. Falls from roof edges were caused by bodily actions and tools. Falls through roof surfaces were caused by detective scaffolding. Falls from ladders were caused by overexertion and unsafe equipment. Falls down stairs were caused by unguarded openings. Falls to a lower floor were caused by poor work practices. Effective primary fall protection consists of fixed barriers, whereas secondary fall protection consists of fall arrest devices and systems. Overall, more males were found to be injured than females and most accidents occurred for workers between 35 and 44 years of age. Most falls occurred in smaller companies, those with fewer than 30 employees.


Fault tree analysis was used to determine the causes of 411 fatal construction falls in Taiwan between 2001 and 2005. The categories that cause falls are: 1) unsafe behavior, 2) unsafe machinery and tools, and 3) unsafe environment. The probability of the causes was determined based on the data collected from the 411 falls. The fault tree also included graphical icons for universal communication.

Chi examined 255 electrical fatalities in construction and analyzed this data based on age, gender, experience, task, environment, company size, injury source, and accident cause. Five major causes of electrocutions were direct worker contact with energized power lines, boom contact with overhead power lines, conductive equipment contact with power lines, worker contact with energized equipment, and defective equipment. The most common victim group was males younger than 35 years old working in smaller firms, those with less than 30 employees.


The combination of unsafe worker acts (misjudgment or inappropriate operation) and unsafe working conditions (unsafe work surface or inclement weather) is one of the main root causes of construction accidents. Chi examines 9,358 accidents in the US construction industry between 2002 and 2011 to determine relationships between worker behavior and working conditions. Human error is defined as an inappropriate decision or behavior that reduces quality or safety, which leads to increased project cost and lengthened project schedule. Heinrich states that unsafe worker acts combined with unsafe working conditions were the root cause of 88% of construction accidents. Unsafe acts include ignorance, lack of knowledge, failure to follow directions, and poor
attitudes toward safety. Human behavior risk factors pertain to worker competence and perception and include judgment/perception, PPE and safety devices, operation procedure, inspection, supervision and engineering control, and safety training. Worksite condition risk factors pertain to tasks and the environment and include action required for task, task regularity, surrounding objects and structure, required tools and equipment, gas, liquid, and solid exposure, layout conditions, temperature, pressure, and noise level, and weather and illumination. Data from the Center for Construction Research and Training shows that the U.S. construction industry employed approximately 8% of the total labor force in 2005 and accounted for 21% of the total fatalities for all industries. This means that three workers die each day on a construction site, which adds up to direct and indirect costs of $5.2 billion. Construction risk can be reduced by identifying related unsafe worker behaviors and unsafe working conditions and separating these. Worker misjudgment led to the most fatalities, and machinery normally led to caught-in/between and struck-by/against incidents.


The relationship between organizational values and safety in high risk industries in Queensland and New South Wales was examined. Organizations that emphasize employee well-being or employee well-being with goal attainment had better safety performance. Organizations emphasizing formal processes and procedures or formal processes and procedures with goal attainment had worse safety performance. The competing values framework focuses on the values of flexibility, control, internal, and external. Balancing all four of these values in makes a work
system safe. This study based on modal profile analysis demonstrates that employee well-being and goal attainment can coexist. The Internal Process model (internal and flexibility) does not coexist with the Human Relations model (internal and flexibility).


Although the perceptions of the importance of safety training are related to actual safety behavior, perceptions and actuality do not always match. A focus on changing unsafe environments and behavior instead of concentrating on attitudes, beliefs, and perceptions is more effective. Safety in this study is based on perceptions of workplace hazards, safety hazards and self-compliance, and safety participation within a manufacturing plant.


Fabius correlates stock market performance with health and safety risks at work based on simulations and past market performance. It argues that companies with better stock market performance have fewer workforce health and safety risks because promoting wellness and reducing health risks within a workforce heavily affects health care costs, productivity, and performance. Fabius writes, “Recently, an article by Loeppke and colleagues reported that for every dollar of medical and pharmaceutical costs spent, and employer lost an additional $2.30 of health-related productivity costs. Companies that create an environment for their employees and
dependents that reinforces both conscious and unconscious safer and healthier lifestyle choices as well as provides more effective accessing of appropriate health care (i.e., surround them with a ‘culture of health’) should be more productive and that productivity should drive business performance and be reflected in the price of their stock”.


Managers promote safe behavior in their employees directly through their behaviors and attitudes and indirectly with a safety management system. The study tested a model for positive safety culture on 455 Spanish companies. Key indicators of an organization’s safety culture include manager commitment, employee involvement, and safety management system.


Gibb emphasizes the importance of tools and equipment in causing accidents. They are a factor in slips, trips, and falls, handling equipment, struck by, injuries directly from tools/equipment, struck against, dangerous occurrences, contact with moving machinery, trapped by collapsing object, contact with electricity, and other. The causal factors such as worker influence, environmental influence, communication, and tool/equipment condition were then examined in each of these categories to determine if an accident was likely or possible.
All organizations must determine what type of safety must be managed, how to manage uncertainty in regards to safety, and regulations for managing safety. Key attributes to consider are personal versus process safety, minimizing versus coping with uncertainty, complex versus routine tasks, homogeneous versus heterogeneous teams, and self versus external regulation.


Hadiprioni studied construction falls from elevated floor openings using a fault-tree expert system to show 17 basic causes, 4 conditional causes, and 28 sets of combined basic and conditional causes. "Improving construction safety performance" states that injury rates for workers in the construction industry is 54% higher than that of all other industries. Construction safety research has focused on procedural, behavioral, and social components rather than engineering components. Hadiprioni uses a system to improve construction safety through an emphasis on the engineering aspects of accidents. The author divides the causes of falls into a number of categories. Worker's enabling causes are attitude, health, and skill-related issues. Worker's triggering causes are human-induced impacts (impacts from equipment, materials, or another worker) and naturally induced impacts (strong winds). Worker's support-related causes are failures from structures and components that support the worker. These are caused by design or construction deficiencies as well as direct impact from equipment. He then created minimal cut sets based on the fault trees.

A sample of 28 out of 211 fatalities in the UK were studied based on reports and interviews and validated based on 50 prior studies. The Human Factors Analysis and Classification System classification of errors and task level factors was used in this study. Contributing causes included inadequate planning and risk assessment, incompetency, improper design and installation, and inappropriate strategy. The most frequent accident types consisted of falls, struck by vehicles, struck by objects, electrocution, collapse, and other.


100 accidents in the UK were studied and it was determined that the accidents were caused by issues on the team, issues concerning the workplace or environment, unsuitable materials and equipment, and poor risk management. There needs to be a greater emphasis on safety, and it must be integrated throughout the project team. Communication and design are key in fixing this problem, and PPE should be the last form of risk management. Companies should spend more time learning from failures through thorough investigations to discover contributing factors earlier in the chain of events.

Construction labor accidents account for 40% of labor accidents in Japan. Literature reviews and field studies were performed in the U.K., Germany, France, U.S., Canada, and Japan to determine labor safety administrative power, labor safety responsibility and costs, accident penalties, accident investigation methods, victim compensation, and manager requirements. Safety is mainly the responsibility of the general contractor in France, Japan, and the U.K., whereas it is an equal responsibility for both the general contractor and the subcontractors in the other countries in this study. All countries are required to carry occupational injury insurance for victims. Similarly, safety managers are required in all six countries. Safety costs are added to total project costs for all countries. Administrative penalties for labor incidents include stopping work and being excluded from public work. Government is usually in charge of safety administration.


Hinze examines the coding system used in OSHA reports and argues that injuries should be coded into the 20 possible cause categories rather than the five groups: falls, struck by, electric shock, caught in/between, and other. Modification of the OSHA coding system will support regulation modifications and delineate the main causes of severe accidents. Previous research in construction safety has focused on safety management but not on field circumstances. OSHA utilizes an Integrated Management Information System (IMIS) to store data from fatalities and serious injuries. OSHA compliance officers write an incident narrative and place the incident in one of the five major categories. These categories are unable to accurately describe the root causes of
accidents, so there is a need for more fitting categories of accident causation to help prevent accidents from occurring. The OSHA cause codes have been modified to include more detail. The 20 cause codes include falls from elevation, falls from ground level, electrocution from power lines, electrocution from building power, electrocution from faulty facility wiring, electrocution from faulty constructions tool/wiring, electrocution from other causes, struck by equipment, struck by material, struck by falling material, struck by material other than falling material, caught in/between equipment, caught in/between material, cave-in, explosion, fire, explosion/fire, asphyxiation, drowning, natural causes, and other. OSHA data was then examined to determine correlations between work type and event type. For instance, equipment-related accidents are generally struck-by or caught in/between, while struck-by accidents usually involve heavy equipment. Work performed near power lines often results in electric shocks.


Hinze discusses the hazardous nature of the construction industry, as it has one of the highest fatality rates among all industries. This is attributed to the nature of construction work, human behavior, construction tools and equipment, and confined work zones. Civil construction, which involves construction of bridges, roads, canals, airports, and other public projects, is one of the most dangerous sectors within construction because more highway construction and maintenance is occurring between dusk and dawn to avoid heavier traffic. In addition, highway construction results in the most vehicle-related accidents. OSHA has improved safety in all occupations by reducing fatalities by 62% and injuries by 42% in the last few decades. This organization enforces regulations and establishes safety standards. Because there are tens of thousands of construction
sites per year and only a few thousand OSHA employees, it is not feasible to examine every construction site. Thus, OSHA compliance inspectors focus on reporting imminent dangers, investigating fatalities, addressing complaints, responding to referrals, and conducting inspections. All non-minor work injuries must be recorded in the OSHA 300 Log. Non-minor work injuries are defined as those that do not require medical treatment other than first aid, do not result in unconsciousness, and do not cause work or motion restriction. These recordable injuries are categorized as lost-time injuries and not lost-time injuries. Hinze researched fatalities with visibility as the main cause. Many visibility accidents involve machinery. A quarter of the fatalities in construction are caused by equipment-related injuries such as collisions, rollovers, and struck-by accidents. Equipment must be inspected prior to use. Even with inspection, operators must be cognizant of other existing hazards. Truck drivers have blind spots when backing up, are distracted when communicating on cell phones and two-way radios, and sometimes choose not to wear high-visibility clothing. Workers can become focused on their work and ignore moving machinery. Discomfort glare can cause discomfort, while disability glare can impair vision. Rain, dust, and dirty or broken windows are further sources of vision impairment. Four times as many accidents occur when reversing than driving forward. Dump trucks are involved in the most accidents because they carry a fully-enclosed bed that creates a large blind spot for the driver. Motor graders have the next highest proportion of accidents because they also have large blind spots and normally operate in conjunction with dump trucks for earthwork. Blind spots are the most frequent cause of visibility-related construction accidents, while obstructions (pile of earth/material) are the second most frequent cause. Other causes include too much lighting (glare/sudden, drastic changes in lighting), too dark (working at night), and moving blind spots. Methods to reduce risks include using a spotter, checking that back-up alarms are fully audible,
and utilizing closed circuit televisions (CCTVs). Understanding the underlying causes of accidents allows for improvements in the construction industry.


Hu performed a literature review on a myriad of papers concerning construction falls and discussed challenge of hazard prevention and control, the poor safety record of construction in comparison to other industries, and the negative impact of falls and other accidents on construction projects. In performing this study, the researchers conducted a literature search for relevant studies, selected those that added to construction fall factors, grouped the findings, and synthesized the results. All studies were published in 1980 or later, and there was a variety of quantitative and qualitative research collected. Once the risk factors were gathered and grouped from the literature review, causes were mapped using different line thicknesses to represent the frequency with which a factor appeared in a paper and using different line type to represent the general consensus on the accuracy of the risk factor. Dotted lines represent many inconsistent views among the literature, dashed lines represent some varying views among the literature, and solid lines represent consistency within the literature. The three most common causes of construction falls were working surfaces and platforms, workers' safety behavior and attitude, and construction structure and facility. The work from this study can be used by construction companies and designers to design more effective safety interventions and reduce the number of work-related falls that occur. It can help policy makers design and modify policies. It can also help workers complete their work more safely.

Huang performed a telephone survey of 404 US corporate financial decision-makers on workplace safety issues. The survey resulted in similar responses from medium and large companies. Their top priorities included overexertion, repetitive motion, and bodily reaction. These are three leading causes of worker’s compensation claims. Major safety concerns were overexertion, repetitive motion, highway accidents, falling on the same level, and bodily reaction. Huang states, “The U.S. Bureau of Labor Statistics (2008) reported that in 2006 there were around 4.1 million nonfatal workplace injuries and illnesses, which means that there were 4.4 nonfatal injuries and illnesses for every one hundred full-time equivalent U.S. workers. In addition, about 5840 fatal occupational injuries occurred in private industry in the U.S. in the same year”. Larger companies believed falling on the same level was a greater concern than highway accidents. The LMWSI reported the ten leading causes of serious workplace injuries (88.1% of direct worker’s comp costs) as overexertions, falls on the same level, bodily reactions, fall from elevation, struck by, highway incidents, repetitive motion, struck against, caught in/by, and assaults/violent acts. A Study from UK Health and Safety Executive estimated indirect costs as 3 to 30 times direct costs. OSHA shows that companies with effective safety and health programs can reduce injury and illness rates by at least 20% and get a return of $4 to $6 for every $1 invested. Improving workplace safety leads to increased productivity and improved financial performance.

Simple accidents are those that may not be reported such as those that do not debilitate employees or only involve one employee. Immediate causes of events include unsafe conditions, unsafe acts, and chance. Unsafe conditions may be design of the work, surroundings, product, or equipment, while unsafe acts may be slips or mistakes. Root causes may be classified as inexperience or lack of training. This is caused by gaps in knowledge, inadequate training, and lack of prioritization. To prevent these accidents from occurring, one must observe, evaluate, and act. For example, observe if PPE is available. Evaluate if it is sufficient. Act by providing sufficient PPE if needed.


Three major factors contribute to injuries. Individual-related factors include age and work experience. Job-related factors include occupation, location, and hazards. Organization-related factors include management support and team size. Interventions can be used to prevent undesired injuries. Engineering interventions are designing for safety. Behavioral interventions are training and education. Enforcement interventions are rules and regulations.


Khakzad provides a comparison between fault tree analysis and the Bayesian network approach in safety analysis, particularly in regards to gas process facilities. It argues that Bayesian networks
are better suited for modeling because they represent event dependency, update probabilities, handle uncertainty, and include expert opinion. Safety analysis involves forecasting likely accident scenarios and quantifying the occurrence probability of these scenarios. Fault trees are tree-shaped graphs with the main event at the top and branches going down to intermediate causes then root or primary causes. They are used to deduce potential causes of an undesired top event, which usually consists of a major accident that causes safety hazards or economic losses. Standard fault trees are not well-suited for the analysis of large systems, especially those with redundant failures, simple failures, and mutually exclusive causes. Some analysis methods for fault trees are the analytical method, the Monte Carlo simulation, and minimal cut-set determination. Bayesian networks are graphs with nodes that represent variables and arcs that represent direct causal relationships between nodes. Conditional probability tables are also attached to each node to show the influence of one node on another node. The chain rule and d-separation criteria is used in Bayesian network analysis. This means that root nodes are conditionally independent, and all other nodes are conditionally dependent on the node directly above them (their direct parent node). One of the main strengths of Bayesian networks is their ability to update the occurrence probability of an event when new or updated information is added. A case study was performed to model a Bayesian network in a propane feeding control system.

The four main accident types in steel construction are falls, object falls, object collapse, and electrocution. A Bayesian network is developed and verified using 15 projects. The root causes for these accident categories were all poor health and safety management.


Mitropoulos takes a systems view of accidents. Production system characteristics create hazardous situations and shape work behaviors. Though the accident rate has decreased over the years, the fatality rate remains constant. Some accident prevention methods include: 1) reliable production planning to reduce task unpredictability and 2) error management to increase workers' ability to avoid, trap, and mitigate errors. Rasmussen's work behavior model states that the workers should work on boundary of safe and hazardous for maximum efficiency. In the accident causation model, arrows represent causal relationships, dotted arrow represent feedback loop, variables in curved boxes, safety strategies in hexagons, + (direct relationship), - (inverse relationship)


Newnam states that road crashes are the most common cause of work-related injuries and deaths in many countries. Work-related drivers are defined as those who drive at least once per week for work purposes, and they have higher crash frequencies. In addition, safety motivation has a lagged effect on safety compliance for up to 2 years.

Odero found that pedestrians and passengers account for 80% of deaths in Kenyan vehicle accidents. Passengers are usually killed on intercity highways, while pedestrians are usually killed in urban regions. Although there has been a 4-fold increase in road fatalities over the last 30 years in Kenya, which has negatively impacted Kenyan economy and healthcare, interventions have been ineffective.


Oz studies the relationship between organizational climate and driver behavior of professional drivers from a questionnaire answered by 230 male professional drivers. Road accidents cause most occupational fatalities in a number of countries. Oz states, “Approximately 25% of the fatal work accidents in Denmark, Finland, and Sweden, and nearly 40% of fatal work accidents in France are road accidents. In Turkey, professional drivers were involved in more than 30% of fatal road traffic accidents in 2009”. Six dimensions can be used to describe an organizational culture: 1) process vs. results oriented, 2) employee vs. job oriented, 3) parochial vs. professional, 4) open vs. closed, 5) loose vs. tight, and 6) normative vs. pragmatic. Driver behaviors can be classified by three items: 1) plan, 2) behavior sequences directed by plan, and 3) extent to which
behaviors are successful in reaching aim. High employee consideration and an emphasis on the organization, work, and rules results in lower driving violations.


962 workers were killed on road construction sites between 2003 and 2010. Almost half of these were stuck by accidents. Training, temporary traffic barriers, speed reduction, an activity area with minimum backing up, and safety planning help to reduce accidents.


Construction safety is affected by poor work and safety organization, company size (too small), poor coordination, money/time pressures, lack of standardization, poor communication, little involvement of works in safety, evolving worksite, worker specialization, looking out for oneself, inadequate training/fatigue, poor equipment selection, use, or inspection, management being unaware of safety, lack of PPE, distance between construction jobs, work stresses. The US construction fatality and disabling injury rate is nearly 3 times that of the all-industry average. Occupational risk assessment requires identifying potential hazards, assessing risks, and determining a hierarchy of risks. Methods can be divided into qualitative and quantitative. Groups can then be divided into deterministic, probabilistic, and deterministic/probabilistic. Deterministic considers the products, equipment, and consequences for people, environment, and equipment. Probabilistic considers the probability of failures on equipment and components. Construction
uses preliminary hazard analysis and checklists often. Preliminary hazard analysis analyzes event sequences that could transform a hazardous energy source, material, posture, environment, etc. into an accident. Jannadi and Almishari defined risk in terms of probability, severity, and exposure to all hazards of an activity. Probability analysis is not suited for construction because probability theory is based on an assumption of randomness and populations, while construction is not random and unique.


Highway workers face risks from both construction vehicles and ongoing traffic during construction. They are at risk of struck-by accidents as well as caught in/between accidents. The unsafe conditions of low lighting, poor visibility, and inclement weather combined with cramped work areas and exposure to traffic pose additional risks for these workers. 58.5% of workplace fatalities occurred in the transportation infrastructure industry between 1992 and 1998. Out of 492 fatalities from highway and street construction between 1992 and 1998, 42% of deaths were construction laborers, 9% were truck drivers, 8% were supervisors, and another 8% were operating engineers. The most common sources of injuries included trucks, road grading and surface machinery, and cars. To reduce the number of highway and street incidents, emphasis should be placed on following the Manual on Uniform Traffic Control Devices published by the Federal Highway Administration. This manual covers specifications for signage, zone markings, temporary traffic control measures, training, PPE, lighting, and speed reduction.

Safety indicators provide information on how an organization is performing and motivating its employees to work safely. Woods and Hollnagel (2006) state that organizations should proactively manage safety, but it is difficult to predict rather than react to hazards. Lagging indicators are most commonly used to indicate safety performance. They are based on historical events. On the other hand, leading indicators anticipate events. Reiman created tables of drive, monitor, and outcome indicators and possible preventative measures. Drive indicators measure organizational safety priorities such as management and leadership. Monitor indicators reflect the organization's potential and capacity for safe performance such as safety and hazard understanding. Outcome indicators measure outcomes of the system such as accident rates.


Rivara evaluates the effectiveness of different prevention strategies for falling from height in construction. Falls account for one-third of construction injuries. Fall from height account for 90% of the falls resulting in recordable incidences. Major risks for falling from height include using ladders and scaffolding, working near floor and wall openings, and working for a small firm with at most ten workers. The inclination angle reduces falls from ladders, fall-arrest devices reduce falls from scaffolding, and safety belts or lines and guardrails reduce falls from roofs.

Suraji uses a constraint-response model, in which the central cause is inappropriate human behavior. It maps potential contributions of all participants within project organization to accident causation process. Constraints include proximal factors or direct causes and distal factors, which increase the risk of accidents. Response can be either action or inaction. This model was validated by studying 500 accident records from U.K. Health and Safety Executive.


Svedung discusses the importance of graphical representations in the causal flow of accidents. Causal trees, event trees, and cause-consequence charts are commonly used for post-event analysis to understand accidents and for predictive risk analysis to design safer systems. These trees and charts focus on technical and human errors, but they fail to include organizational and social factors. The Management Oversight and Risk Tree (MORT) includes these factors. Pro-active risk management strategies are more beneficial than reactive risk management strategies based on analysis of historical accidents. The authors have developed graphical representations that structure hazardous tasks with the inclusion of sociological and technical aspects. These maps can be used to support both field work and safety audits by showing preconditions, functions, and contributions. The cause-consequence chart demonstrates a group of plausible or actual events, in which causes are connected to the main event with or gates and decision switches show human
decisions. Analyses are based on accident committee reports. These charts show all possible situations for a hazard, while causal trees show causes from previous accident investigations. The AcciMap represents a specific accident scenario using a cause-consequence chart, environmental stressors, and a representation of the people involved in the planning, management, and regulation of this situation. The Generic AcciMap is a collection of AcciMaps from a specific type of hazard and includes which parties should be studied during their routine work. The ActorMap identifies the contributing parties from the AcciMap as well as those involved in the planning and risk management of the work. The InfoFlowMap illustrates how information flows between decision makers.
### 9.2 OSHA ROOT WORD DEFINITIONS

Table 9.1 OSHA Root Word Definitions

<table>
<thead>
<tr>
<th>Phrase</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Hazardous Worksite</td>
<td>working conditions and environment prevent hazards to workers</td>
</tr>
<tr>
<td>Inadequate Design</td>
<td>design does not follow guidelines and leads to unstable structure</td>
</tr>
<tr>
<td>Inadequate PPE</td>
<td>not wearing the minimally required amount of personal and protective equipment</td>
</tr>
<tr>
<td>Inappropriate Position</td>
<td>not using the correct position for a task</td>
</tr>
<tr>
<td>Inappropriate Procedure</td>
<td>not following the correct procedure for a task</td>
</tr>
<tr>
<td>Insufficient Training</td>
<td>not having adequate training for a task</td>
</tr>
<tr>
<td>Lack of Engineering Controls</td>
<td>not having appropriate design or enclosures to reduce or eliminate hazards to workers</td>
</tr>
<tr>
<td>Miscommunication</td>
<td>not communicating effectively with other workers</td>
</tr>
<tr>
<td>Misjudgment</td>
<td>not utilizing correct judgment</td>
</tr>
<tr>
<td>No Spotter</td>
<td>not having a safety observer designated for watching out for electrical hazards</td>
</tr>
<tr>
<td>Poor Layout</td>
<td>ineffectively arranging a worksite</td>
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